

Assessment of the Energy Efficiency of Cyclic High-Pressure Reagent Injection Systems Compared with Continuous-Operation Plunger Pumps

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Abstract— The article presents a comparative assessment of the energy efficiency of cyclic high-pressure reagent injection systems and continuous-operation plunger pumps used for anticorrosion protection of oil and gas well equipment under high pressure, elevated temperature, and chemically aggressive multiphase media. The relevance of the study is determined by the need to solve simultaneously two interrelated tasks: maintaining a stable protective inhibitor film on the metal surface and reducing energy, material, and operating costs associated with reagent dosing. The aim of the work is to provide scientific and techno-economic substantiation of the advantages of cyclic dosing over traditional continuous and periodic injection schemes. The scientific novelty of the article lies in the integrated comparison of three technological approaches based on operational, economic, and physicochemical parameters, as well as in the interpretation of intermittent injection efficiency in terms of adsorption kinetics and the film lifetime effect. It has been established that cyclic systems maintain anticorrosion efficiency at 94% while reducing commercial inhibitor consumption by 73.6%, decreasing energy consumption, lowering pump equipment wear, and diminishing total operating costs. It is shown that switching pumps to a short-time, repeated-duty operating mode using hydraulic accumulators and intelligent control results in a more rational and technologically stable reagent injection regime. The article will be useful to researchers, oil and gas engineers, specialists in corrosion protection, automation, and energy-efficient technologies for field infrastructure.

I. INTRODUCTION

Ensuring the reliability and integrity of downhole equipment and pipeline transport systems constitutes one of the most critical tasks in the contemporary oil and gas industry (Khan et al., 2021). The global depletion of conventional, easily recoverable hydrocarbon reserves determines the transition to the development of deeply buried horizons, including deeply buried high-pressure

horizons of Western Siberia (Saitova et al., 2023). The average reservoir pressures are 60-70 MPa and temperatures regularly exceed 100 °C. The corrosive environment is the result of a high aggressiveness of the produced fluid as a result of a high partial pressure of carbon dioxide and the presence of highly mineralized formation waters (Sergeeva et al., 2025). Under the conditions of a multiphase medium, the corrosion of the tubing and

flowlines due to the joint action of carbon dioxide and hydrogen sulfide is exponential, leading to through-wall perforation of tubing and flowlines in months if no preventive solutions are used (Rahmawati et al., 2021).

The most economic method of corrosion and erosion-corrosion wear prevention is continuous or periodic chemical dosing with corrosion and hydrate suppression inhibitors (Gharbi et al., 2021), in which the main mechanism is the formation of a nanometer thick chemisorbed corrosion protective film on the metal surface acting as a diffusion barrier between the aggressive aqueous phase and the steel substrate. However, the efficiency of this method is also determined by the technology applied in the delivery and distribution of the reagents (Kokalj, 2022).

Chemical reagent injection systems have undergone significant technological evolution over time. Initially, the batch treatment method dominated, requiring well shutdowns and the deployment of heavy, specialized equipment to inject large volumes of inhibitor and methanol. This approach was distinguished by colossal operating expenditures and a high carbon footprint (Pan et al., 2022). It was subsequently replaced by skid-mounted, continuous-operation cluster units based on multihead plunger pumps. Despite process automation and the elimination of manual labor, continuous-operation systems revealed new vulnerabilities. The continuous operation of electric motors results in low energy efficiency, while continuous reagent injection into a high-velocity fluid stream leads to excessive chemical consumption, much of which does not have time to adsorb onto the walls and is carried away to separators (Li et al., 2023).

A modern response to these challenges has been the development of cyclic intermittent high-pressure dosing systems controlled by programmable logic controllers and equipped with hydropneumatic accumulators. This concept presupposes pump operation in a duty cycle to charge accumulators, from which the reagent is delivered smoothly and with high precision to wells through electrically actuated valves.

Despite the technological interest of cyclic systems, there is a lack of work in the literature concerning the direct evaluation of economic efficiency and physicochemical film formation models under intermittent injection conditions (Shwetha et al., 2024). Current works only limit themselves to the chemical design of the inhibitor, pump hydraulics, and other aspects without considering the synergy of the whole system (Bijapur et al., 2023). The relevance of this study is determined by the need to scientifically substantiate the transition of fuel and energy enterprises to energy-saving dosing technologies.

The research problem concerns the existing technological contradiction: on the one hand, maintaining the continuity of the anticorrosion film is intuitively associated with continuous reagent injection. On the other hand, the requirements for energy efficiency and OPEX optimization demand minimizing pump equipment operation and reducing injected chemical volumes.

The aim of the article is to scientifically and technoeconomically substantiate the advantages of cyclic high-pressure reagent injection systems over continuous-operation plunger pumps in terms of energy efficiency, reduced inhibitor consumption, lower operating costs, and preservation of anticorrosion protection under high-pressure, aggressive conditions in oil and gas wells.

To achieve this aim, the following objectives were set:

- To analyze the features and shortcomings of the traditional method of periodic reagent pumping from the standpoint of chemical consumption, labor costs, involvement of special equipment, and the level of operating expenditures.
- To investigate the operational and technological limitations of continuous-operation systems based on plunger pumps for reagent injection under conditions of high pressures and aggressive media.
- To consider the design and functional features of cyclic high-pressure dosing systems and determine their differences from traditional and continuous reagent injection schemes.
- To assess the economic and energy efficiency of cyclic systems in comparison with alternative reagent injection methods on the basis of operational data and total cost analysis.
- To determine the practical advantages of implementing cyclic dosing systems from the standpoint of reducing inhibitor consumption, increasing equipment reliability, decreasing OPEX, and preserving the required level of anticorrosion protection.

The scientific novelty of the article lies in the integrated comparison of periodic, continuous, and cyclic reagent injection systems, based on operational, economic, and technological indicators simultaneously considered. The work demonstrates that cyclic dosing enables high anticorrosion efficiency while substantially reducing inhibitor consumption, energy use, and wear on pumping equipment.

II. MATERIALS AND METHODS

To ensure representativeness, verifiability, and high scientific reliability of the results, the present work employs a comprehensive methodological apparatus. The research design is constructed around methods of comparative analysis of hydrodynamic and physicochemical processes, the case study method applied to specific industrial facilities, and the analysis of design, technical, and operational documentation.

Due to non-disclosure agreement obligations, the names of the field, wells, equipment manufacturers, and specific unit model designations have been anonymized throughout this paper. Continuous-operation and cyclic high-pressure dosing systems of two different domestic manufacturers are referred to as Unit A and Unit B, respectively.

The study's informational and empirical basis is structured into three key groups of sources that form the foundation for the theoretical, market, and practical parts of the analysis.

The first group consisted of internal reporting and technical documents that reflected the actual operating conditions of equipment at deeply buried high-pressure gas-condensate fields of Western Siberia.

The data for assessing the resource intensity of the traditional method were obtained from the analytical summaries, Table of Volumes and Costs of Chemical Reagents for 1 Well Pumping Cycle, and the logs Calculation of Pumping Operations. Corrosion Inhibitor Pumping. Consolidated Register for 2026. These materials contain the precise geometry of 21 wells, including lengths and diameters, calculations of the volumes of injected methanol and inhibitor, payroll estimates, and the cost of machine-hours for special equipment. The assessment of continuous-operation systems was based on the minutes of a commission meeting of a gas-production company on the completion of pilot industrial operation of a corrosion inhibitor solution injection unit manufactured by a specialized domestic dosing equipment producer (hereinafter referred to as Manufacturer A). The document contains gravimetric metrics of anticorrosion protection efficiency, failure statistics, including leakage through the sealing package at the 144th hour of operation, and defect inspection reports on the condition of plunger pairs. The operating manual of the corresponding multihead plunger dosing unit (hereinafter referred to as Unit A) was also examined.

Technical documentation from a specialized engineering company (hereinafter referred to as Manufacturer B) was used to analyze the operation of the cyclic systems, including the operating manual of the cyclic high-pressure dosing block (hereinafter referred to as Unit

B), the operator's manual, P&IDs, and the data arrays of flow rate and pressure changes from the log of observations of operating parameters of the inhibitor injection block at a gas-condensate cluster of the studied field for the period from January to April 2026.

The second group included mathematical and physicochemical approaches. Total cost of ownership was determined as the sum of capital costs, chemical reagent operating costs, energy consumption, and maintenance costs, providing economic efficiency. To substantiate the protection mechanism under intermittent injection, the Langmuir thermodynamic model was used to describe the kinetics of surfactant monolayer formation at the metal–fluid phase boundary. The calculation of energy efficiency was based on comparing the integral work performed by electric motors in continuous and short-time, repeated-duty operating modes.

The third group of sources includes a review of current academic literature for 2021–2026 indexed in the international scientometric databases Scopus, Web of Science, IEEE, and Springer. These studies were used for an in-depth understanding of the film lifetime phenomenon and the influence of hydrodynamic shear stress on inhibitor desorption. Academic literature also served as the basis for assessing the corrosion aggressiveness of multiphase media. It confirmed the validity of intermittent dosing from the standpoint of multiphase flow hydrodynamics.

The integration of the indicated methods and sources enabled the formation of a closed analytical contour in which field empirical data receive rigorous physicochemical and economic interpretation.

III. INDENTATIONS AND EQUATIONS

The logic of presenting the research results is structured around the historical and technological evolution of well equipment protection systems: from manual, periodic treatment methods to continuous mechanical systems and, finally, to intelligent cyclic complexes. Such an approach makes it possible to demonstrate most vividly the qualitative leap in energy efficiency and OPEX reduction.

3.1. Techno-economic profile of the traditional method of periodic pumping

Historically, the dominant method of inhibiting gas and gas-condensate wells not equipped with stationary chemical injection lines was periodic pumping (Askari et al., 2021). The technological process consists in temporarily shutting down the well, followed by connecting a mobile pumping unit, for example, a CA-320 or its analogues, and injecting into the tubing or annulus a massive slug mixture of corrosion inhibitor and hydrate formation inhibitor,

methanol. It is expected that, upon subsequent well start-up, this volume of liquid will distribute itself over the inner surface of the lift string, forming a protective film.

Analysis of volumes and costs of chemical reagents for 1 well pumping cycle enabled quantification of the resource

intensity of this approach. The required reagent volume is calculated individually based on the lift string's geometric volume. Table 1 presents data for the five most resource-intensive wells from the analyzed sample of 21 wells.

Table.1: Reagent consumption and its cost per pumping cycle

Well Number	Lift Length, m	Volume, m ³	Methanol Consumption, m ³	Inhibitor Consumption, m ³	Reagent Cost per Cycle, RUB
Well 1	290	1.385	1.108	0.277	66,350.69
Well 2	245	1.170	0.936	0.234	56,054.89
Well 3	214	1.022	0.818	0.204	48,962.23
Well 4	213	1.017	0.814	0.203	48,733.43
Well 5	204	0.974	0.779	0.195	46,674.28

Note: Methanol density is 0.7 kg/l, price is 18,837 rubles/t; inhibitor density is 0.923 kg/l, price is 202,368 rubles/t.

For the pool of 21 wells, the total reagent cost for one pumping iteration amounts to 653,508.53 rubles. Under the standard maintenance schedule, implying weekly treatment over 50 weeks per year, i.e., 1050 well operations, annual expenditures create a critical burden on the enterprise's OPEX.

In addition to direct chemical costs, the method is tied to human labor and the logistics of heavy equipment. Labor input per operation amounts to 8 man-hours, i.e., a crew of 2 persons. At a payroll rate of 1,567.97 rubles/hour, annual personnel expenses reach 26.34 million rubles. In parallel, the operation of special equipment, 8 machine-hours per cycle at a rate of 4,815 rubles/hour, costs 40.44 million rubles per year.

The consolidated economic model of the traditional method is depicted in Fig. 1. Total annual OPEX approaches 100 million rubles.

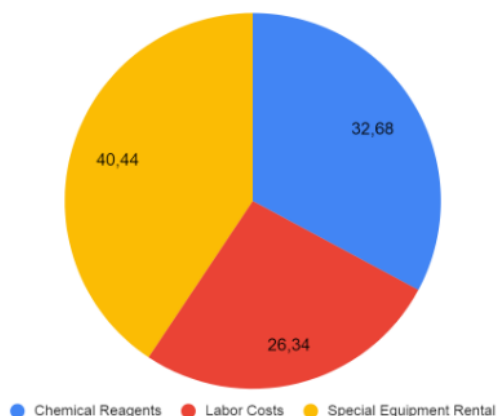


Fig. 1: Structure of the annual OPEX method of periodic pumping, million RUB

In addition to economic insolvency, the batch treatment method is subject to serious criticism in contemporary academic literature for its hydrodynamic and corrosion-engineering shortcomings (Li et al., 2023). Slug injection forms a nonuniform film. Under the influence of high hydrodynamic shear stress in the multiphase gas-condensate flow, the adsorbed inhibitor layer is gradually washed away (Ezeh & Oriaku, 2020). During the intervals between pumping cycles, closer to the end of the week, the well remains virtually unprotected against carbon dioxide corrosion, rendering the expediency of massive chemical injections moot. Furthermore, the use of diesel pumping units runs counter to modern ESG standards due to high greenhouse gas emissions (Babamohammadi et al., 2025).

3.2. Technological barriers of continuous-operation units: Unit A

Recognition of the inefficiency of manual labor led the industry to implement stationary skid-mounted units (Mubarak et al., 2023). The object of analysis is a multihead diaphragm unit of a specialized domestic manufacturer (Unit A). The apparatus represents a classical positive-displacement plunger-type pump with a crank-and-rod mechanism that converts the rotation of the asynchronous electric motor rotor into the reciprocating motion of the plungers.

The implementation of these units enabled the Elimination of the costs of special equipment and operator daily labor from the Total Cost of Ownership structure. The results of pilot industrial operation at one of the gas-condensate clusters of the studied field confirmed the high technological viability of the method: the delivery coefficient was ≥ 0.9 with an error not exceeding 10%, and

the final efficiency of anticorrosion protection reached 94% according to gravimetric control results.

Nevertheless, the analysis of the pilot industrial operation results and the theoretical foundations of the process reveal two critical systemic limitations of continuous-operation units.

The first is mechanical degradation and wear under high loads. The plunger pump is forced to continuously overcome high formation backpressure, which in deeply buried gas-condensate horizons reaches 50–64 MPa. Constant friction in sealing assemblies under extreme pressure accelerates elastomer wear. According to the defect inspection reports from the pilot operation protocol, leakage of the highly toxic inhibitor solution through the plunger sealing package occurred after only 144 hours of operation, i.e., 6 days of continuous service. Further element-by-element disassembly revealed abrasive wear of the plunger itself, manufactured from stainless steel 12Kh18N10T. To arrest the problem, modernization was required, namely a transition to 40Kh13 steel with hardening or ceramic coating, as well as the use of hard-alloy valves. This indicates that the continuous operating regime drives the mechanical part of the pump to the limits of the fatigue strength of materials.

The second limitation is the substantial overconsumption of chemical reagents. Statistics showed that over a month of continuous operation, the unit injects 1322.8 kg of a 10% corrosion inhibitor solution, which is equivalent to 132.28 kg of the 100% commercial reagent form. Such colossal consumption is determined by adsorption kinetics. Under continuous injection, the inhibitor concentration in the flow is excessive. The pipe surface has a finite area, and after the formation of a monomolecular layer, a steric hindrance effect arises (Wang et al., 2022). The remaining volume of expensive surfactant is physically incapable of binding to steel and is uselessly carried by the hydrocarbon flow to the gas treatment unit,

where it may moreover cause emulsion stabilization problems.

From an energy standpoint, continuous rotation of electric motors with power ratings of 5.5 to 7.5 kW or higher for multihead units creates a permanent base load on the field power grid, which does not meet energy efficiency criteria.

3.3. Architecture and functional indicators of cyclic cyber-physical systems: Unit B

The response to the mechanical and chemical limitations of continuous systems was the development of cyclic dosing complexes (Unit B) manufactured by a specialized engineering company (Manufacturer B).

The fundamental distinction of this system lies in the integration of high-pressure pumps with buffer pneumatic-hydraulic accumulators RSV1–RSV6 and an intelligent control system based on the Siemens S7-1200 PLC with an OVEN SP310 HMI panel.

Unlike Unit A, where the pump injects directly into the well, the pumps in the cyclic system operate in a duty cycle. When the pressure in the system falls, the automation starts the pump, which, at maximum efficiency, forces inhibitor into the hydraulic accumulators, compressing the nitrogen contained therein according to Boyle–Mariotte’s law to the upper setpoint limit, for example, to 20 MPa. After this, the pump is switched off, and the active phase is completed.

Thereafter, the passive phase begins: the accumulated potential energy of compressed nitrogen smoothly expels the inhibitor into the wells through a network of individual throttles DRN1–DRN10 and high-precision electrically actuated control valves KR1–KR5. Coriolis or thermal flowmeters RXM1–RXM5 provide continuous feedback to the PLC, maintaining a precision flow rate of 0.5–50 l/h with an accuracy of $\pm 2\%$. An operational diagram of an intelligent dosing system with a hydraulic accumulator is shown in Fig. 2.

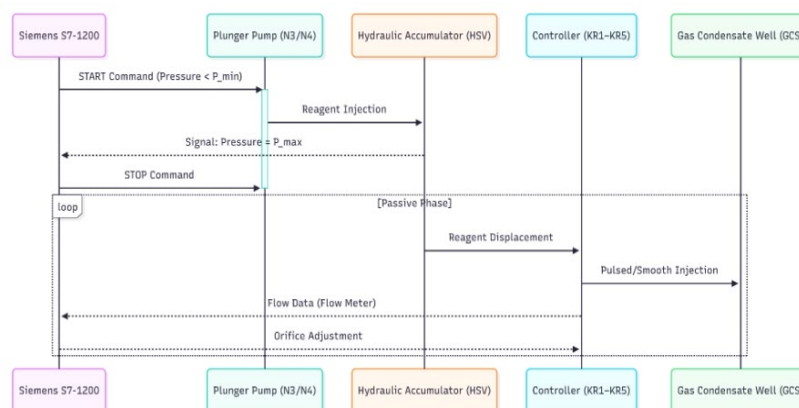


Fig. 2: Operational diagram of an intelligent dosing system with a hydraulic accumulator

The log of observations of operating parameters for January 2026 demonstrates the highest system adaptability. The block successfully serves wells with radically different characteristics. Thus, at one of the served clusters, the injection pressure was maintained at 18.4–19.1 MPa, with a daily consumption of about 43.2 kg. In parallel, at an adjacent cluster, the injection pressure ranged from 26.2 to 26.7 MPa. The intelligent separation of flows after the hydraulic accumulator makes it possible to maintain the required differential, a delta of more than 8 MPa, without overloading the central pump.

The principal technological breakthrough was the reduction in reagent consumption. Over a month, the cyclic unit consumed 1135.2 kg of a 3% solution, which is equivalent to 34.9 kg of the 100% commercial inhibitor form.

3.4. Physicochemical substantiation of cyclic efficiency

The possibility of reducing the consumption of the active chemical substance by 73.6%, from 132.28 kg to 34.9 kg, without loss of protective properties, i.e., ensuring preservation of 94% efficiency, represents a rigorous consequence of the laws of the physical chemistry of surface phenomena, as confirmed by recent studies (Liu et al., 2026).

Modern corrosion inhibitors, as a rule, are nitrogen-containing organic compounds, imidazoline derivatives, and amines, which are chemisorbing surfactants. They contain a polar head that chemically binds to iron cations on the pipe surface and a long hydrophobic hydrocarbon tail that repels the aqueous phase (Sriplai & Sombatmankhong, 2023). The process of their deposition is described by the Langmuir isotherm:

$$\theta = \frac{K_{ads} \cdot C}{1 + K_{ads} \cdot C} \theta = \frac{K_{ads} \cdot C}{1 + K_{ads} \cdot C},$$

where θ is the fraction of the surface covered by the inhibitor, K_{ads} is the adsorption equilibrium constant,

and C is the volume concentration of the inhibitor in the fluid.

Under continuous injection, as in Unit A, the concentration is artificially overstated. The film forms instantaneously, after which the surface becomes physically saturated. All subsequent inhibitor molecules undergo steric repulsion and are carried away by the flow.

Cyclic injection is based on the concept of desorption hysteresis and film lifetime. The formed imidazoline monolayer possesses significant bond energy; therefore, it is not washed away instantaneously even under high hydrodynamic shear stresses arising in turbulent gas-liquid flow (Sriplai & Sombatmankhong, 2023).

Under cyclic dosing, the system introduces a calculated micro-dose of inhibitor sufficient to ensure $\theta \approx 1$. Thereafter, the injection is reduced to a minimum or stopped. During this passive phase, the film slowly degrades due to desorption and erosion. The PLC software is configured to deliver the next reagent pulse exactly when the degree of coverage approaches the critical threshold, before corrosion has begun. This allows permanent protection while using 3.8 times fewer chemicals.

3.5. Economic synthesis and metrics of energy efficiency

A comparison of the three technological paradigms enables a transparent matrix of energy efficiency and operating costs.

First, material efficiency. The implementation of the cyclic system enables saving 97.38 kg of commercial inhibitor per month per cluster, i.e., 132.28 kg – 34.9 kg. At a market reagent cost of 202,368 rubles/t, the cost avoidance is 19,706 rubles per month, or 236,480 rubles per year per unit. When scaled across the entire well stock of a large field with hundreds of clusters, tens of millions of rubles are released solely through savings on chemical procurement, as shown in Table 2.

Table.2: Comparative matrix of the efficiency of dosing systems

Parameter	Periodic Pumping, Special Equipment	Continuous Operation, Unit A	Cyclic Operation, Unit B
Drive Operating Mode	Intermittent, ICE	100% Duty Cycle, S1	Intermittent Cyclic, S3
Inhibitor Consumption, per month	Extreme, hundreds of kg	132.28 kg	34.9 kg
Reagent Savings, vs Unit A	–	Baseline	–73.6%
Plunger Pair Wear	Not applicable	High, failure after 144 h	Low, increased MTBF
Personnel / Logistics Costs	Over 66 million RUB/year	Eliminated	Eliminated
Automation & Telemetry	None	Local	Advanced, Siemens S7-1200

Second, energy efficiency and mechanical life. Energy savings in the cyclic system (Unit B) are achieved by shifting electric motors from continuous mode to short-time repeated-duty mode. Although the peak installed power of the block may reach 30 kW, which includes block-box heating, instrumentation, and drives, the pumps themselves operate for only a small fraction of the daily time. The integral monthly electric energy consumption in kWh is substantially lower than that of constantly operating 5.5–7.5 kW motors in units of Unit A type.

A reduction in the duty cycle coefficient exponentially increases the mean time between failures. The risk of catastrophic wear of the sealing package, recorded in Unit A on the 6th day, is neutralized in the cyclic system, since the plunger performs tens of times fewer friction cycles.

3.6. Barriers, risks, and limitations of implementing cyber-physical complexes

Despite the obvious advantages, the transition to cyclic systems of this level poses several engineering and managerial challenges that must be considered during design and operation.

First, there is high capital intensity and structural complexity. The P&ID diagrams of such blocks demonstrate the presence of numerous precision components: hydraulic accumulators, electrically actuated valves, throttle packages, and mass flowmeters. This increases the initial cost of equipment procurement compared to simple plunger pumps.

Second, there are cyber-physical vulnerabilities and dependence on instrumentation and automation. The system's efficiency depends entirely on the correct functioning of the Siemens S7-1200 PLC and flowmeters. Failure of a pressure sensor or controller freeze may lead to either injection shutdown, which creates a risk of rapid corrosion, or overdosing. A high level of qualification among instrumentation engineers is required to service HMI interfaces and calibrate PID controllers.

Third, there are operational risks of gas-hydraulic systems. The use of accumulators RSV1–RSV6 charged with nitrogen to 14–20 MPa creates a potential hazard of explosive failure in the event of maintenance regulations violations. Gas leakage through a damaged accumulator membrane into the hydraulic circuit can disrupt the dosing logic and require a lengthy depressurization and recharge procedure.

Fourth, there are explosion protection requirements. The block boxes are installed in hazardous areas of class 1 or 2. All components, from Metran sensors to electric drives, must possess Exd/Exib certification. Any breach of

enclosure tightness during the current repair fatally reduces facility safety.

IV. CONCLUSION

The study demonstrates that the technological evolution of chemical reagent injection systems in the oil and gas sector is profoundly deterministic. The audit showed that traditional periodic pumping methods exhibit critically low indicators of economic and operational efficiency, resulting in unjustified costs of about 100 million rubles per year for a small group of wells and failing to ensure reliable, permanent pipeline protection.

The transition to stationary continuous-operation plunger-pump units (Unit A type) solved the problem of manual labor, yet revealed new barriers: accelerated abrasive wear of mechanical assemblies, seal leakage at the 144th hour, and colossal reagent overconsumption, up to 132.28 kg of commercial inhibitor per month, caused by the impossibility of adsorption of the excessive volume of chemicals on pipe walls.

Based on analyses of operational log data for a representative gas-condensate cluster and technical documentation, it has been established that cyclic cyber-physical systems (Unit B) represent the most advanced technological paradigm to date. The use of buffer hydraulic accumulators in conjunction with a PLC enabled the transfer of pumps to a short-time, repeated-duty operating mode. This solution significantly improved the units' energy efficiency and extended the service life of mechanical parts.

The principal scientific and practical conclusion lies in the fact that intermittent dosing, based on the physicochemical principles of adsorption kinetics and desorption hysteresis, the so-called effect of preserving film lifetime, makes it possible, without compromising infrastructure integrity and while maintaining 94% protection, to reduce the consumption of the base corrosion inhibitor by 73.6%, i.e., to 34.9 kg per month. This indicator yields direct annual savings of hundreds of thousands of rubles per cluster.

Despite the increased requirements for the competence level of instrumentation and automation maintenance personnel and the higher capital costs associated with the complex hydropneumatic architecture, the total cost of ownership of cyclic complexes is significantly lower. Thus, the implementation of cyclic automated high-pressure dosing systems is an economically, energetically, and technologically substantiated vector for the development of the modern resource extraction industry.

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